

PRELIMINARY RESULTS FROM THE PROCESSING OF A LIMITED SET OF GEOSAT RADAR ALTIMETER DATA

Data obtained during the geodetic phase of GEOSAT provide a unique opportunity to represent the mean sea surface and compute accurate information about anomalous aspects of the earth's gravitational field. Observations and summary statistics obtained from the processing by the Defense Mapping Agency Aerospace Center of a limited amount of GEOSAT radar altimetry data are presented. Statistics from comparisons of mean gravity anomalies computed using GEOSAT data and corresponding values obtained using the best available survey data are shown. Future plans and directions for the continued processing and exploitation of the data are discussed.

GEOSAT DATA PROCESSING SYSTEM

General

The satellite radar altimetry group at the Defense Mapping Agency Aerospace Center (DMAAC) has taken an active role in identifying and addressing the tasks associated with the final stages of processing and developing GEOSAT data into gravimetric products. Major products include adjusted along-track geoid heights, gridded geoid heights, and mean gravity anomalies.

The group's main activities include editing, adjusting for the residual radial orbit error, and storing in an on-line database for ready access. Regular shipments of GEOSAT filtered geophysical data have been received from the Naval Surface Weapons Center (NSWC) since mid-October 1985. The data are processed in seven-day data sets of approximately 660,000 data records each. By November 1986, 17.2 million GEOSAT data records had been processed by DMAAC and stored in 120 15- \times 30-degree "minifiles" of bit-packed, area-sorted data records.

Editing

A comprehensive automated program compares the computed geoid heights, the deflections of the vertical, and all significant data corrections with predetermined bounds. Rates of change of the gravimetric quantities and corrections are also monitored to guard against discontinuities. Flags are set during this procedure to identify the nature and severity of the condition detected. Each revolution of data is profiled and compared with the best available gridded geoid-height data and with available bathymetry. Flag conditions also trigger profile plots of a selected set of up to nine data corrections. To aid editing, the along-track geoid-height profiles can be projected onto three-dimensional reference surfaces

that include known seamount locations. A follow-on interactive edit program allows the analyst to view in detail any portion of a revolution with its associated data records, to view immediately the results of an edit action, and to iterate the activity if necessary.

The GEOSAT data processed thus far have been remarkably clean and have required minimal editing. Less than 1.5 percent of the GEOSAT data received from NSWC have been flagged for exclusion from further processing.

Adjustment

In what is essentially a geometric computation, the computed geoid heights depend directly on a precise orbit determination. Residual radial orbit errors reveal their presence as differences from one pass to another in computed along-track geoid heights at subsatellite points. These differences are referred to as crossing-point differences and directly reflect the degree of self-consistency of the data. While earth gravitational models and orbit determination procedures have significantly improved (the precise orbits were computed by NSWC using the World Geodetic System 1984 Earth Gravitational Model), some uncertainty remains. The 1.04-meter preadjustment crossing-point statistic (Table 1, discussed below) for intersecting passes of ascending and descending GEOSAT along-track data supports the idea that the individual orbits have radial uncertainties of less than 1 meter.

An adjustment procedure that uses an assumed error model minimizes the computed geoid-height differences at points where GEOSAT ground tracks cross each other and where they cross a carefully constructed reference network. This geoid-height reference network was constructed from Seasat data collected during the final three weeks of the satellite's operating life while it was in a repeat-track configuration. Geophysicists at the Naval Oceanographic Office averaged the multiple data along

The author is with the Defense Mapping Agency Aerospace Center, St. Louis, MO 63118.

Table 1—Summary of GEOSAT geoid-height-adjustment statistics (17,296,452 processed GEOSAT points).

<i>Preadjustment Statistics</i>		
<i>WGS 84 GEOSAT geoid heights compared to WGS 84 (n=m=180) geoid heights</i>		<i>rms of GEOSAT/GEOSAT geoid height crossing-point differences</i>
<i>Number of comparisons</i>	<i>Mean of differences</i>	
1,071,813	-0.10 meter	1.04 meters
<i>Postadjustment Statistics for Individual Seven-Day Data Sets</i>		
<i>rms of GEOSAT/GEOSAT geoid height crossing-point differences</i>	<i>rms of GEOSAT/reference network geoid height crossing-point differences</i>	
0.13 meter	0.22 meter	
<i>Postadjustment Statistics for All Possible GEOSAT/GEOSAT Crossing-Point Differences for Data Processed</i>		
<i>Number of points</i>	<i>Mean of crossing-point differences</i>	<i>rms of crossing-point differences</i>
1,783,837	-0.005 meter	0.206 meter

these repeat tracks and adjusted them into a highly self-consistent data set. The network was further modified at DMAAC by filling in sparsely covered areas and increasing the density of the network arcs in known trouble spots. The enhanced network serves as a control for adjusting the GEOSAT data tracks. The network approach has been used successfully by a number of investigators and is well documented in several reports (e.g., Ref. 1).

The adjustment model used at DMAAC is a three-parameter (bias, tilt, and bend) model that has constant, linear, and quadratic terms and that uses the local time along the arc as the independent variable. Arcs are subdivided into ascending and descending parts and are further restricted to lengths shorter than those traversed within 2000 seconds. Data gaps of up to 500 nautical miles are allowed before the segment following the gap is defined as a different arc. The inclusion of the quadratic term in the error model is particularly effective in aligning longer arcs; however, the linear and quadratic terms make the adjustment process susceptible to the aliasing of oceanographic phenomena into the process. Aliasing can become serious for short arcs; in order to monitor the problem, limits are imposed on the magnitudes of the adjustment parameters so that they conform to expected bounds for radial orbit uncertainties and rates of change. An additional measure of control is ob-

tained by requiring a minimum number of crossings of the unadjusted arcs with themselves and with the geoid-height reference network.

The adjustment phase is a critical part of the data processing in that the long-wavelength, along-track orbit error can manifest itself as a short-wavelength random error that occurs when revolutions adjusted during different times and having different residual error characteristics lie close together in a geographic area. A random selection of points can cause fairly large signals of short wavelength to appear. Then, a data-rich environment provides the opportunity to average the data and to exercise statistical selectivity, thereby reducing the adverse effects of adjustment misalignment (and of other random errors as well). Careful editing and adjustment pay dividends because recovery of the mean gravity anomaly from the geoid height data is, in a sense, an amplification process, and relatively small geoid-height errors propagate into sizable errors in the recovered mean gravity anomalies.

Adjustment statistics are summarized in Table 1 for the data processed. They show a 13-centimeter postadjustment rms for GEOSAT minus GEOSAT ground-track crossings and an average of 22 centimeters for GEOSAT minus Seasat reference network ground-track crossings. The GEOSAT minus GEOSAT statistics increase when the individually adjusted sets are combined and the resulting mixture is tested. Cumulative postadjustment statistics for the entire 17.3-million-point data set involving more than 1.78 million crossing points show a mean of very nearly zero and an rms of 21 centimeters.

The statistics in Table 1 also show the cumulative results of the differences between the sampled along-track GEOSAT geoid heights before adjustment and the geoid heights computed using a spherical harmonic expansion and the World Geodetic System 1984 Earth Gravitational Model through degree and order 180. Assuming the so-called "oceanic" definition of the geoid, whereby the mean sea-surface topography over the oceanic areas is taken to be zero, the statistics indicate the compatibility of the spherical harmonic-derived and "observed" GEOSAT geoid heights, at least with respect to the overall scale. The agreement to within 10 centimeters is important for applications where gaps in the altimetric geoid heights are filled in or otherwise buffered by spherical harmonic-derived values.

An anomalous situation surfaced while the comparison statistics were being generated. During the analysis, it was noted that the ascending and descending portions of the data arcs did not yield the same statistics. In addition, the results computed on a week-to-week basis changed significantly (Fig. 1). However, the situation does not seem to affect data-adjustment efforts adversely, and the individual data sets appear to be driven successfully to the Seasat network.

One aspect of network adjustment deserving comment is that the network imposes its scale and other long-wavelength characteristics on the geoid driven to it, meaning that deficiencies in the Seasat network will bleed into the GEOSAT geoid adjusted to it. Conversely, gravity anomalies derived from GEOSAT data will ben-

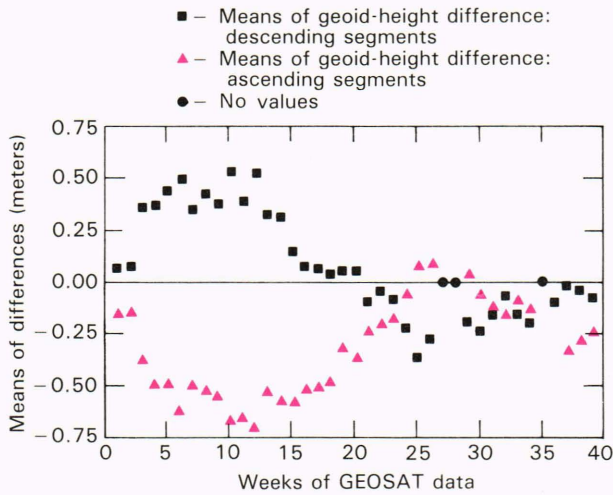


Figure 1—The variation in the means of differences between geoid heights from ascending and descending segments of GEOSAT's revolutions (both sets are compared to WGS 84 ($n = m = 180$) computed for consecutive seven-day data sets.

efit from improvements that can be made to the reference network. This process is a critical, limiting factor in improving the recovery of mean gravity anomalies from altimeter data. If a new GEOSAT network is forthcoming from the GEOSAT Exact Repeat Mission, it will be profitable to readjust the GEOSAT data using the new network.

AN INTERIM GEOSAT GEOID-HEIGHT DATA SET

The fully processed GEOSAT geoid heights adjusted to the World Geodetic System 1984-related Seasat reference network are maintained in the minifile database. The data are readily accessed by utility subroutines that permit the selection of points by attribute and also by statistical comparison with the point data within a selected geographic cell size. The individual points chosen are those that agree best with the average of the points in the cell after those geoid heights that deviate from the average values by more than two sigma have been excluded. These statistically selected points are referred to as "most representative values" for the cell size specified. The results from the comparison of mean gravity anomalies obtained using geoid heights from various data-thinning procedures with "truth" mean gravity anomalies indicate the value of using these most representative geoid heights. Since values obtained for the computed mean gravity anomalies are quite sensitive to the geoid heights used in calculating them, statistical procedures designed to reduce random errors will continue to be explored and the results evaluated.

With an along-track resolution that is about the same as Seasat and that has a low noise level, a 15- × 15-minute grid was used for the initial production of GEOSAT gridded geoid-height data sets. In May 1986, a preliminary gridding was done using approximately 12 million points. "Most representative" values for 5- × 5-minute cells were used to produce a geoid-height val-

ue for the center of each 15- × 15-minute cell using the statistical Wiener-Hopf prediction process. This gridded geoid very clearly showed trench, seamount, fracture, and ridge areas and appeared to be free of the adjustment difficulties often experienced with altimeter data from GEOS-3 and Seasat. The 15- × 15-minute gridded values were then averaged into 1- × 1-degree mean geoid heights and used to compute 1- × 1-degree mean gravity anomalies.

For a number of reasons, the random error in the geoid, as implied by postadjustment crossing-point statistics, is not necessarily a reliable indicator of the true level of random error in the gridded geoid. The crossing-point differences represent the combined effects of the errors in both the ascending and descending arcs used to compute the differences. One might be tempted to divide by $\sqrt{2}$ to obtain an improved estimate of the level of random error in the along-track geoid-height data. Also, error levels are reduced by using the statistically chosen points and by the smoothing associated with the gridding process.

COMPUTATION OF MEAN GRAVITY ANOMALIES

Several techniques have been used by various investigators to compute mean gravity anomalies from altimetric geoid heights. The Inverse Stokes Method and least-squares collocation² have been among the more successful ones. Although they have been used in the past at DMAAC and by others, the technique selected for use with the GEOSAT data is a modification of the Molodensky integral,

$$\Delta g_p = - \frac{\gamma N_p}{R} = \frac{\gamma}{2\pi} \int_{\sigma} \frac{N - N_p}{r_p^3} d\sigma,$$

where Δg_p is the gravity anomaly calculated at the computation point p , γ is the mean value of theoretical gravity, N_p is the geoid height "observed" at point p , R is the mean radius of the earth, r_p is the chord distance between the computation point and a differential surface element $d\sigma$ that has "observed" geoid height N , and the summation extends in principle over the surface of the earth. This formulation has a distinct advantage over other approaches in that it does not require the inversion of a matrix. It is referred to here as the direct integration method.

Early estimates of the recovery capabilities of the direct integration method were pessimistic.³ Large errors were estimated for workable (tractable) cap sizes of 5 to 6 degrees due to the omission of observed geoid-height data outside the cap. The strategy used to reduce the error is to represent it analytically in such a way that the functional representation can be incorporated into the gravity-anomaly computation and the remainder minimized. The use of truncation coefficients together with an accurate spherical harmonic-derived reference geoid to represent a portion of the missing geoidal information outside the cap area is described by Jekeli⁴

and by Gaposchkin in Ref. 5, which gives a formation that is close to that developed at DMAAC. While these modifications have greatly reduced the error of omission, additional stress is placed on the geoid data available for use in the mean-gravity-anomaly calculation in that the modified kernel becomes more responsive to data errors. For the results discussed here, a 6-degree cap was used with the above equation for Δg_p , and a spherical harmonic expansion through degree and order 12 provided the reference geoid.

INTERIM MEAN GRAVITY ANOMALIES DEDUCED FROM GEOSAT DATA

Full sets of 1- × 1-degree and 30- × 30-minute mean gravity anomalies were generated in the ocean areas to within 2 to 3 degrees of land, using means of the 15- × 15-minute gridded geoid heights described earlier. The generated 1- × 1-degree mean gravity anomalies were then compared with similar values computed from the best available gravity survey data (Table 2). The mean gravity anomalies compared represent gravimetrically smooth, intermediate, and rough areas. Use of cosine window weighting in the averaging of the 15- × 15-minute geoid heights improved the results. However, the direct computation of 30- × 30-minute mean gravity anomalies and the averaging of them into 1- × 1-degree values agreed best with the 1-degree values obtained from the gravity survey data. For that method, no 5- × 5-degree area showed a sigma for the differences greater than four milligals. Both methods 2 and 3 (Table 2) have the beneficial effect of diminishing the aliasing resulting from the straight averaging of the 15-minute gridded geoid heights in the 1- × 1-degree areas to obtain 1- × 1-degree mean geoid heights. In

the future, attention will be given to the generation of 15- × 15-minute mean geoid heights with benefits expected in gravity anomaly accuracy from the use of the smaller size cells.

OCEANOGRAPHIC AND BATHYMETRIC CHARACTERISTICS NOTED FROM THE GEOSAT DATA

The North Atlantic area off the east coast of the United States has often been identified as one of strong dynamic sea-surface topography. The Gulf Stream current, eddies, cold rings, and a high level of variability in the mean sea surface are all associated with the region. The unusually large postadjustment crossing-point differences observed there (37 centimeters rms) are possible indicators of such dynamic effects.

Bathymetric features are beginning to be resolved in the 30- × 30-minute mean-gravity-anomaly field. An image made from the 30- × 30-minute means in the North Atlantic (Fig. 2) shows details of the mid-Atlantic ridge and several fracture zones.

CONCLUSIONS AND FUTURE DIRECTIONS

Although only approximately one-third of the available GEOSAT data have been processed and used to date (November 1986) by DMAAC, the Navy's GEOSAT Program can unequivocally be proclaimed a huge success. The management and technical expertise exercised by involved Navy organizations and APL have produced an oceanic altimetric data set of unparalleled accuracy.

Efforts will be directed toward reducing errors in the geoid heights, taking advantage of the data-rich environ-

Table 2—GEOSAT-derived 1- × 1-degree mean gravity anomalies with "truth" compared with 1- × 1-degree values computed from gravity survey data (interim values based on 17 weeks of GEOSAT data).

Mean-Gravity Anomaly Computation Method	Number of Values Compared	Mean-Gravity-Anomaly Differences					
				Maximum		Number of differences	
		rms	Mean	Positive diff.	Negative diff.	>10 milligals	>20 milligals
1*	4534	2.7	0.33	23.4	-28.2	37	3
2†	4534	2.3	0.34	14.4	-18.8	16	0
3‡	4523	2.1	0.34	11.2	-13.3	6	0

Description of GEOSAT geoid-height input data used in mean-gravity-anomaly computations:

*1- × 1-degree mean geoid heights obtained as a simple average of the 15- × 15-minute gridded geoid heights available within each 1- × 1-degree area.

†Same as method 1 except obtained using a cosine window weighting.

‡30- × 30-minute mean geoid heights obtained as a simple average of the 15- × 15-minute gridded geoid heights available within each 30- × 30-minute area. Heights were used to compute mean gravity anomalies, which were then averaged to obtain 1- × 1-degree mean gravity anomalies.

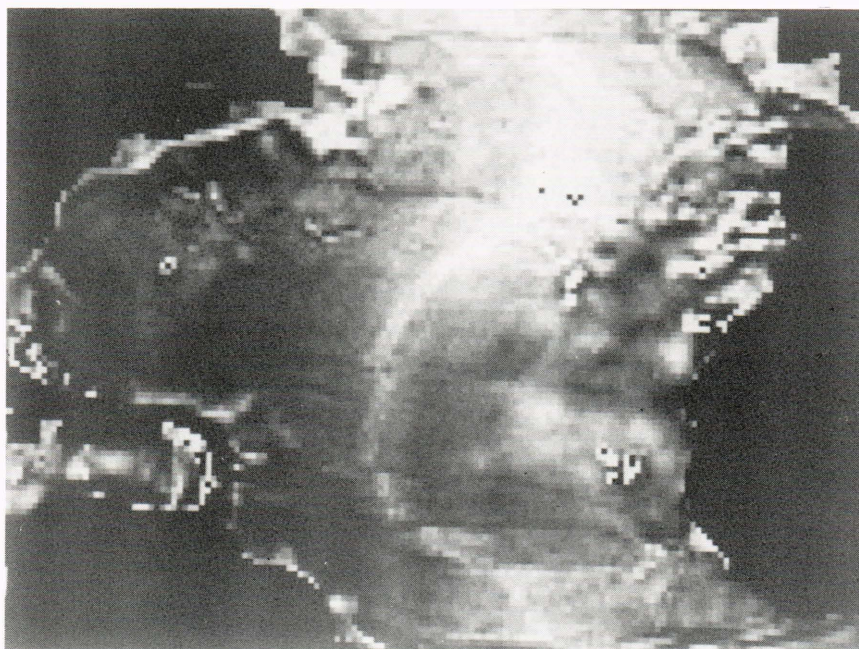


Figure 2—An image of a GEOSAT 30- × 30-minute mean-gravity-anomaly field (North Atlantic area).

ment provided by the full complement of GEOSAT data. A 7.5- × 7.5-minute gridded geoid will be produced and 15- × 15-minute mean gravity anomalies computed and evaluated. Any developments in the modeling of oceanographic effects, particularly the quasistationary currents, will be reviewed for possible application. Improvements expected from a network of GEOSAT repeat-track data are eagerly awaited.

Mean gravity anomalies obtained from the GEOSAT data compared more favorably with mean gravity anomalies developed from ship gravity data than any previous altimetry-derived results, including those achieved from a combination of GEOS-3 and Seasat data (using any computational strategy). It is also evident, however, that much work remains if the full potential of this rich GEOSAT data set is to be realized.

REFERENCES

- ¹ D. Rowlands, *The Adjustment of SEASAT Altimeter Data on a Global Basis for Geoid and Sea Surface Height Determination*, Department of Geodetic Science and Surveying Report No. 325, Ohio State University, Columbus (1981).
- ² C. C. Tscherning and R. H. Rapp, *A Fortran IV Program for the Determination of the Anomalous Potential Using Stepwise Least Squares Collocation*, Department of Geodetic Science and Surveying Report No. 212, Ohio State University, Columbus (1974).
- ³ J. J. Buglia, *The Effects of Remote Zones on the Accuracy of Evaluating the Molodensky Integral*, TM X-72796, National Aeronautics and Space Administration (1976).
- ⁴ C. Jekeli, *Reducing the Error of Geoid Undulation Computations by Modifying Stokes' Function*, Department of Geodetic Science and Surveying Report No. 301, Ohio State University, Columbus (1980).
- ⁵ E. M. Gaposchkin, *Geodetic Use of GEOSAT-A*, AFGL-TR-83-0254, Air Force Geophysics Laboratory (1983).